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GEOLOGICAL SURVEY OF NEW SOUTH WALES.

PROBLEMS
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ARTESIAN WATER SUPPLY OF AUSTRALIA:

WITH
SPECIAL REFERENCE TO PROFESSOR GREGORY'S THEORY.

BY

E. F. PITTMAN, A.R.S.M.,
GOVERNMENT GEOLOGIST OF NEW SOUTH WALES.

[*Clarke Memorial Lecture, delivered before the Royal Society of New South Wales, 31st October*, 1907.]

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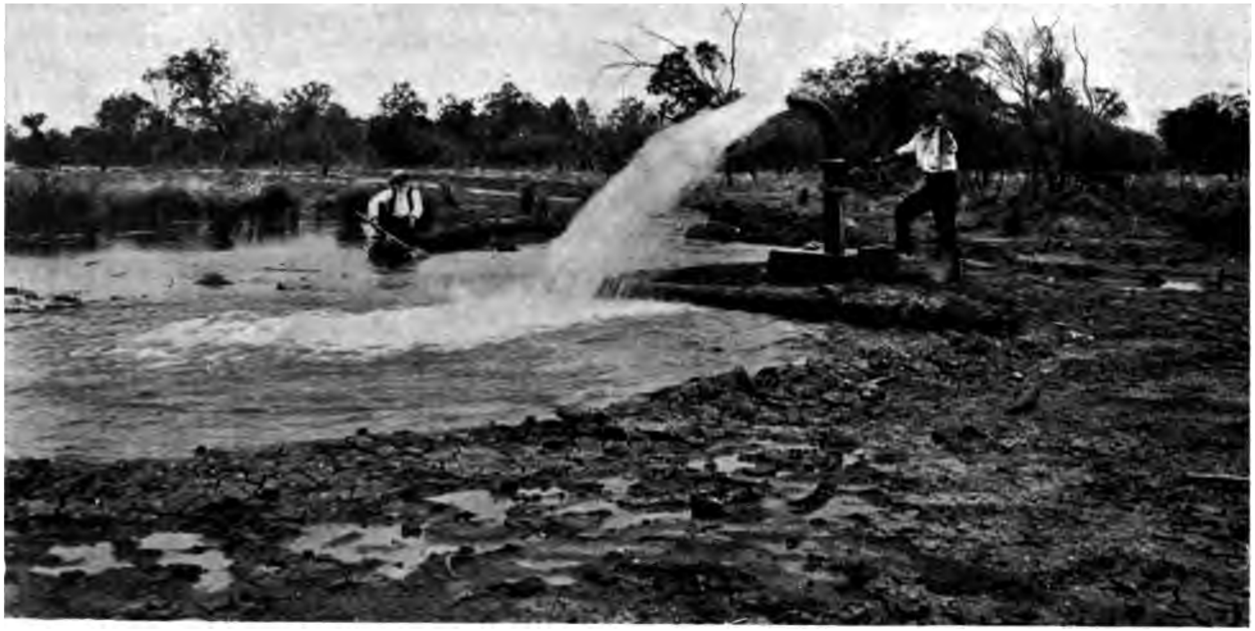
Plate I.



E. F. Pittman, Photo.

ARTESIAN WELL, YARRAWIN STATION, BREWARRINA DISTRICT
Depth 1,472 feet. Yield 688,800 gallons per day.

PROBLEMS
OF THE
ARTESIAN WATER SUPPLY OF AUSTRALIA:
WITH
Special Reference to Professor Gregory's Theory

[By E. F. PITTMAN, A.R.S.M., Government Geologist of New South Wales.]

[Plates I—III.]

[Clarke Memorial Lecture, delivered before the Royal Society of New South Wales, 31st October, 1907.]

In certain localities, when bore-holes are put down in the earth's crust, considerable volumes of water rise above the surface like fountains, and form a more or less permanent supply. These are termed artesian wells, after Artesium, the Roman name of one of the provinces of France, where the first artesian bore was put down. In these cases the phenomenon is accompanied by certain geological conditions, and the rise of the water is due to well-recognised laws.

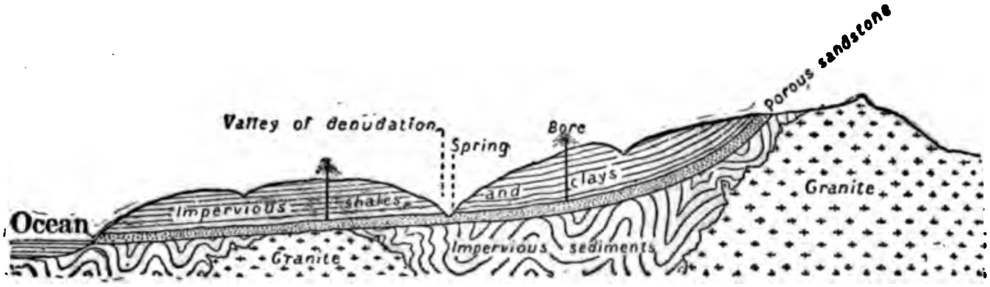


Fig. 1.—Ideal section of an Artesian Basin with leakage to the ocean, and also to a valley of denudation.

The best treatise extant on the occurrence of artesian water was published by Professor T. C. Chamberlin, of Chicago University, in 1885.[*] In this monograph he gives the following statement of the conditions necessary for artesian wells :—

I. A pervious stratum to permit the entrance and the passage of the water.

II. A water-tight bed below to prevent the escape of the water downward.

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[*] Ann. Rept. U. S. Geol. Survey, 1885, v, pp. 125–173.

III. A like impervious bed above to prevent escape upward, for the water, being under pressure from the fountain head, would otherwise find relief in that direction.

IV. An inclination of these beds, so that the edge at which the waters enter will be higher than the surface of the well.

V. A suitable exposure of the edge of the porous stratum, so that it may take in a sufficient supply of water.

VI. An adequate rainfall to furnish this supply.

VII. An absence of any escape for the water at a lower level than the surface of the well.

With regard to Condition III, it may be observed that the artesian basin of Perth, Western Australia, is believed to have no continuous impermeable covering, nevertheless the water rises well above the surface in bores. Attention was drawn to this fact by the writer in 1901, and it was suggested that where even porous sand rocks form the upper strata of a basin, they offer such resistance to the vertical ascent of the water that if a bore be put down to the water-bearing bed a flowing well may result from the sudden relieving of the pressure.*

In 1905 Mr. M. L. Fuller, an eminent American geologist, also described the occurrence of artesian water at Long Island, New York, in some gravel and sand beds which have no impervious covering. He stated that, according to Mr. A. C. Veatch, "the occurrence of flows depended upon slight differences in the degree of porosity of the sands, which, however, were in all cases pervious throughout."†

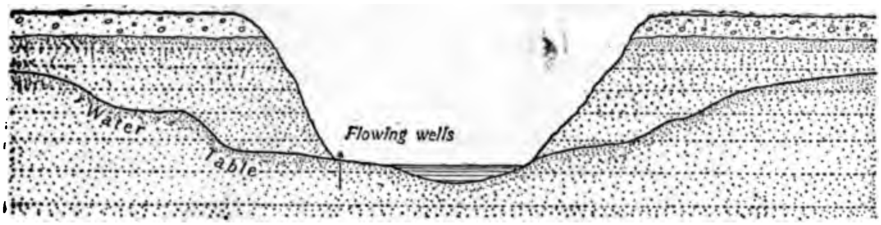

Fig. 2.—Diagrammatic east-west section across the bays on the north shore of Long Island, New York, showing horizontal stratification of beds (gravels and sands), form of water table, and position of flowing wells.—"Hydrology of Eastern United States," 1905, p. 41.

It appears, therefore, that an impermeable covering is not an absolutely necessary condition for an artesian basin, although it is present in most large basins.

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* E. F. Pittman, The Mineral Resources of New South Wales, 1901, p. 458.

† M. L. Fuller, Contributions to the Hydrology of Eastern United States, 1905, U. S. Geol. Survey, Water Supply and Irrigation Paper, No. 145, pp. 40-41.

Professor C. S. Slichter has suggested* that Chamberlin's Condition VII should be amended to read "an absence of any *easy* escape for the water at a lower level than the surface of the well."

The necessity for some such amendment is apparent when it is remembered that some artesian basins have leakage to the sea, while in others the porous water bearing beds are intersected by valleys of denudation, thus providing an escape for the water at a level which is lower than the surface of the flowing wells. In these cases it is clear that the resistance which the porous beds offer to the lateral flow of the water is sufficient to preserve the necessary head.

With the slight amendments just referred to, the conditions prescribed by Chamberlin in 1885 may be accepted as governing the occurrence of artesian water.

In the great Australian artesian basin, which comprises considerable portions of the States of Queensland, New South Wales, and South Australia, the observations of local geologists have established the fact that the conditions just referred to prevail. There are the porous sandstones of the Triassic Coal Measures (and in places the overlying Blythesdale Braystones) outcropping at considerable altitudes in Queensland and New South Wales, on the flanks of the Main Dividing Range, and dipping westward under the Central Australian plains; there are the underlying impervious rocks (granites and altered Palæozoic sediments) which form the floor of the basin; there are the overlying impervious strata which cover the porous sandstones to a depth of several thousand feet; and, lastly, there is an adequate rainfall, averaging about 25 inches per annum, in those districts where the porous beds are exposed at the surface. No one has succeeded in disproving the existence of any of these conditions, and it may be stated that the only material detail in which the Australian differs from any other well-known basin is in regard to its much greater dimensions. There has therefore been no hesitation in ascribing the ascent of the underground water in the Australian basin to hydrostatic, or more properly, hydraulic pressure.

Recently, however, this conclusion has been severely criticised by Dr. J. W. Gregory, F.R.S., formerly Professor of Geology in the University of Melbourne, but now of the University of Glasgow. In consequence of his great reputation as a geologist, and the distinguished position which he occupies, Professor Gregory's opinions are entitled to respect and consideration; nevertheless, there is evidence that his views in regard to this matter are not based upon personal investigation. It is understood that the only part of the Australian artesian water-bearing area examined by him was the desert country in the vicinity of Lake Eyre, in South Australia, and that he has never visited Queensland or that portion of New South Wales where the porous intake beds are visible at the surface. It follows, therefore, that he is not in a position to speak with authority upon the geology of this interesting problem, and as many of his statements appear to be in opposition to observed facts they cannot be allowed to pass unchallenged.

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* Water Supply and Irrigation Papers No. 67, U. S. Geol. Survey, "The Motions of Underground Water" (Slichter), 1902, p. 82.

Professor Gregory's first criticism of the views of Australian geologists was given in a lecture at Bendigo (Victoria), in 1901.* He asserted that in the case of the Australian artesian basin the hydrostatic head must be lost, owing to friction, long before the bores are reached; he contended that the real cause of the ascent of the water was local, and could be explained by reference to the action of geysers; that artesian flow is, in most cases, due to the earth's internal heat, the water being given off from cooling igneous rocks; that the artesian bore through the upper impermeable strata relieves the pressure on the heated water, and that its expansive force and imprisoned gases compel it to rise to the surface.

In a paper read before the Royal Society of New South Wales in 1903,† Mr. Knibbs combated the views of Professor Gregory, and showed that—

> "Hydrostatic head never disappears by friction;" that "the rate of loss of hydrostatic head depends upon the rate of flow, and is very small when the velocity is small," and that "the earth's internal heat is not the chief cause of the ascent of the water, as proved by the fact that the pressure is never relieved so far as to allow of ebullition."

In 1906 Professor Gregory published a very interesting book,‡ in which he states at considerable length his reasons for disagreeing with the conclusions of Australian geologists in regard to the great artesian basin. He asserts that the water of our flowing wells is plutonic and not meteoric—that it has, in fact, never previously appeared at the surface, and that its rise is due to the influence of *temperature* and *rock-pressure.*

It is not proposed to discuss here, at any length, the general question as to the probability of very large bodies of underground water being of plutonic origin, *i.e.*, of their having been given off by cooling deep-seated igneous rocks. Suffice it to say that the view adopted by most American geologists, viz., that "*all* underground waters have their origin in rainfall," has much to commend it. The material point to be argued here is as to whether the *artesian water supply of the Australian basin* has been derived from rainfall, and has been stored in the porous sandstones under hydrostatic or hydraulic pressure, or whether, as contended by Professor Gregory, it has been evolved from underground masses of igneous rocks, and is forced above the surface in bores by the influence of temperature and rock-pressure. The Professor refers to the "simplicity" of the former hypothesis as if it were something reproachful, but it is generally conceded that a simple explanation of a geological problem is to be preferred to one involving far-fetched or complicated reasoning.

It is proposed to deal first with the objections urged by Gregory against the hydrostatic-pressure theory, and then to consider the theory which he propounds in lieu of it.

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* "Variation of ores in depth—the controlling factors," *Australian Mining Standard*, December 12 and 26, 1901.

† G. H. Knibbs, F.R.A.S., "The Hydraulic Aspect of the Artesian Problem," Journ. R. Soc. N. S. Wales, xxxvii, 1903, pp. xxiv-xliv.

‡ The Dead Heart of Australia, by J. W. Gregory, F.R.S., D.Sc. London, John Murray, 1906.

Loss of Head through Friction.—The objections are based upon both physical and chemical considerations, and the principal one is that, owing to the great distance (600 miles) which the water would have to travel underground between the intake beds on the flanks of the Dividing Range and the bores at Lake Eyre, friction would cause the disappearance of the whole of the head.*

So far as is at present known, the Australian artesian basin is the largest in the world, but there are some other well-known basins of very respectable dimensions. For instance, the Paris basin is about 100 miles wide,† while the water-bearing beds of the Dakota basin extend for about 350 miles.‡

The Hon. Dr. G. Otis Smith, Director of the United States Geological Survey, writes under date July 13, 1907 §:—

> The questions raised have been referred to Mr. M. L. Fuller, who has had charge of artesian water investigations in a considerable portion of the country for a number of years. His statements are as follow:—"The greatest distance which water is known to travel underground in the United States is in the St. Peter sandstone, the water entering the intake area in the southern part of the State of Wisconsin at an altitude of about 875 feet, and flowing at an altitude of 575 feet in Central Kentucky, 450 miles to the south-east. In an open porous sandstone of this type the loss of head is very slight, amounting to only about ·67 of a foot per mile, and there is no reason to believe that the water might not penetrate and give flows at a distance of 1,000 miles or more if the porous beds were continuous."

In view, therefore, of the fact that water is known to travel underground in America for a distance of 450 miles, it is difficult to understand why the possibility of its flowing 600 miles in Australia, under analogous conditions, should be so emphatically denied.

Gregory is of opinion that in ascribing the rise of the water in our Australian wells to hydrostatic pressure Australian geologists have under-rated the resistance to the flow of water through rocks due to friction,‖ and he considers that as the water has to percolate, not through open tubes, but through the very minute pores of rocks which are under the pressure of some thousands of feet of overlying material, friction would soon obliterate the whole of the head.

If this opinion were correct, it would be impossible to accept the theory of hydrostatic pressure to account for flowing wells in any of the larger artesian basins of the world; but its incorrectness can be easily demonstrated by extracts from Professor Gregory's own book. He quotes¶ from Box's "Hydraulics" to show that a 1-inch pipe discharging a gallon of water per minute will lose, owing to friction, 700 feet of head in a distance of 100 miles, and he asserts that if the water were flowing through sand instead of a pipe it would lose very much more head. He had previously* referred to the Grenelle Bore, in the Paris Basin, as an example of a flowing well in which the ascent of the water is *really due to hydrostatic pressure.* Now, according to Prestwich† and Daubrée,‡ the width of the Paris Basin—or, in other words, the distance between the intake-beds at Champagne and the Grenelle Bore—is just about 100 miles; therefore, if the water flowed between those two places through a 1-inch pipe instead of through the Lower Greensands, there would be a loss of 700 feet of head in the distance, and (according to Gregory) as the water actually flows through sand, the loss of head should be very much more. But Prestwich states§ that the difference in altitude between the Champagne Hills and the Grenelle Bore only averages about 261 feet; therefore the water at Grenelle should not rise (if Gregory's view be correct) within at least 439 feet of the surface, whereas it actually rises 120 feet above the surface, or would, if it were allowed to rise in an open pipe. It appears, also, that the loss of head in this instance is only about 136 feet (instead of 700 feet) in 100 miles.

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* The Dead Heart of Australia, pp. 300–305.

† Prestwich, Quart. Journ. Geol. Soc., 1872, XXVIII, p. lix.

‡ C. S. Slichter, The Motions of Underground Waters. Water Supply and Irrigation Papers, U. S. Geol. Survey, No. 67, p. 56.

§ Personal communication.

‖ The Dead Heart of Australia, p. 300.

¶ *Ibid.*, p. 303.

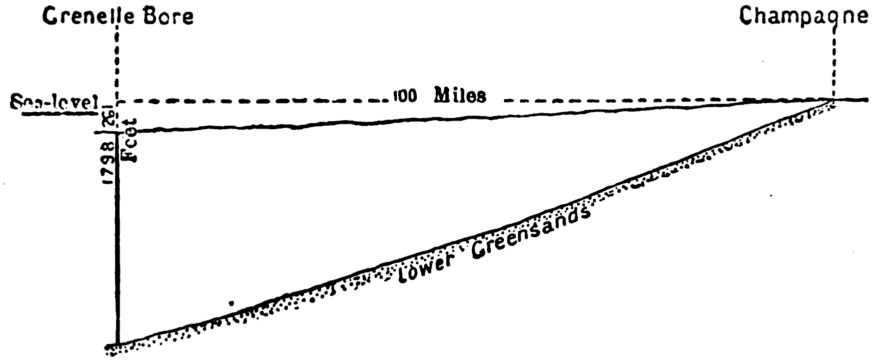

Fig. 3.—Diagrammatic section of the Paris Artesian Basin.

Rate of Flow of Underground Waters.—It is clear, therefore, that either the flowing bore at Grenelle is not caused by hydrostatic pressure, or that the loss of head, in the case of water traversing porous rocks, is nothing like 700 feet in 100 miles. Let us inquire into the latter statement. Gregory argues that, inasmuch as the loss of head in pipes increases, owing to friction, as the diameter of the pipes decreases, it follows that in porous rocks the loss of head must rise to a maximum, because the interstitial spaces represent pipes of exceedingly small diameter. The answer to this is that the loss of head also increases approximately as the *square* of the velocity,* and that, therefore, velocity is a much greater factor in determining loss of head than is either the distance travelled or the diminution of the diameter of the pipes; and the head is therefore maintained in artesian basins owing to the extremely slow rate of flow of the water in the porous beds. Knibbs has shown† that in a uniform stratum the velocity diminishes, as the distance from the bore is increased, in the ratio $\frac{r}{R}$, where r is the radius of the bore and R the distance of the point considered: that is to say, putting v for the velocity at the bore of radius r, and V for that at the distance R from its centre, $V = \frac{vr}{R}$. Consequently, if a 6-inch bore discharges with a velocity of 5½ feet per second from a porous bed of uniform thickness, the velocity of the water in the porous bed at a distance of one mile from the bore would be $\frac{1}{320}$ inch per second, or 22½ feet per day; if the distance be increased to 5 miles, the velocity of the water in the porous bed would be reduced to 4½ feet per day. In short, we may conceive that, in the first instance, the water in an artesian basin would, unless there were a natural outlet, be practically without motion: in this case the pressure would be hydrostatic; then the putting down of bores would induce a flow, with high velocity in their immediate vicinity, but decreasing gradually to an infinitesimal rate of movement as the distance from the bores increased. The pressure would thus become hydraulic.

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* The Dead Heart of Australia, p. 282.

† Prestwich, Quart. Journ. Geol. Soc., 1872, XXVIII, p. lix.

‡ Daubrée, Les Eaux Souterraines, Vol. I, 1887, p. 209.

§ *Op. cit.*

It would appear, therefore, that Professor Gregory, being impressed by the great velocity of the water as it rushes from the bores, has much overestimated its rate of flow in the porous beds remote from the influence of the bores.

In connection with this question, it is interesting to note that Professor Slichter has made a number of accurate determinations of the rate of movement of groundwaters in America.‡ He used for this purpose an ingenious apparatus designed by himself. Several test wells are bored at short distances apart along the approximate course of the flow. The up-stream well is charged with a strong electrolyte, such as sal ammoniac, and as the solution passes down stream with the moving groundwater it forms a good electrolytic conductor of electricity. Each of the down-stream wells contains an electrode consisting of a nickeled brass rod, and electrical connection is made between the casings of all the test wells. As the electrolyte solution moves in the direction of the down-stream well the electric current between it and the up-stream well gradually rises, mounting rapidly when the electrolyte begins to touch the down-stream well. When the electrolyte finally reaches and enters the down-stream well it forms a short circuit between the casing of the well and the electrode, causing an abrupt rise in the current, which is recorded by an amperometer. By using three down-stream wells instead of one, the direction of the flow, as well as its velocity, can be determined.

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* The Dead Heart of Australia, p. 302.

† G. H. Knibbs, "The Hydraulic Aspect of the Artesian Problem." Journ. R. Soc. N. S. Wales, XXXVII, 1903, p. xxx.

‡ C. S. Slichter, Field Measurements of the Rate of Movement of Underground Waters. Water Supply and Irrigation Paper No. 140, U. S. Geol. Survey, 1905.

The following are the results of twenty-seven determinations made by Professor Slichter,* at Long Island, New York :—

Number of Station.	Depth of Wells in inches.	Velocity of ground-water in feet per day.	Number of Station.	Depth of Wells in inches.	Velocity of ground-water in feet per day.	Number of Station.	Depth of Wells in inches.	Velocity of ground-water in feet per day.
1	22	5·5	7	20	2·6	15	42	1·53
2	22	2·	8	21·6	0	15x	62·5	6
2x	22	6·	8	21·6	3·1	16	16	0
3	22	2	10	28	2·6	16x	16	77·
4	22	2	11	22	0·	16x	16	11·6
5	22	6·4	12	27	1·07	17	20	10·6
5x	22	5·4	13	16	96·	18	62	1·
5y	22	8	13	16	6·9	21	16·5	21·3
6	34	5	14	17	9·3	22	16	5·6 ?

The mean rate of flow of the twenty-seven determinations was 11·05 feet per day. The same writer has made determinations, by the chlorine and other methods, of the rate of movement of the underflow beneath the channel of the Arkansas River, in Western Kansas.† He says :—

> Six miles below Garden, at a level of 10 feet below the river bed, the velocity was found to be 2½ feet per day. The fall of the river is about 7 feet per mile. The material below the 10 feet level is coarser than that above, and the velocity is undoubtedly higher. Determinations of the rate of underflow in the narrows of the Hondo and San Gabriel Rivers, in Southern California, by the author's critical method, gave rates of 3½, 4, 5½, and 7 feet per day.

According to M. L. Fuller,‡ the loss of head in the water percolating the St. Peter sandstone, in the States of Wisconsin and Kentucky, amounts to only ·67 feet per mile. If it be assumed that the same rate of loss prevails in the Triassic sandstones of the Australian artesian basin, and there is no apparent reason why it should not, the total loss of head between the Queensland hills and the bores around Lake Eyre would only amount to about 400 feet; there is, therefore, nothing remarkable in the ascent of the water in those bores, in view of the high altitudes at which the porous beds outcrop on the flanks of the Queensland hills.

In the light of what has already been said, it is evident that Professor Gregory's objections to the hydrostatic pressure theory, so far as they are based upon the distance which the water has to travel, and the loss of head by friction, cannot be sustained.

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* C. S. Slichter, Field Measurements of the Rate of Movement of Underground Water. Water Supply and Irrigation Paper No. 140, U. S. Geol. Survey, 1905.

† C. S. Slichter, The Motions of Underground Waters. Water Supply and Irrigation Papers, U. S. Geol. Survey No. 67, 1902, p. 43.

‡ Personal communication already referred to.

Other objections which he urges refer to apparent anomalies in regard to the temperature and pressure of the artesian wells. It must be admitted that remarkable differences of temperature and pressure do occur, and that it is not easy to give an explanation which is capable of definite proof; nevertheless several possible explanations can be advanced, and it may be stated that the anomalies to which the Professor draws attention are not confined to the Australian basin, having been observed elsewhere.

Anomalies in Temperature.—Gregory states* that "the hottest water does not come from the deepest wells. The water of the Clifton and Tinaroo wells is of the temperature of 139°, whereas the deepest well of this series is at Wallon, and its water is only 124°, and the well at Moree, 2,792 feet deep, has a temperature of 115°. . . The average increase of temperature below the surface of the ground is generally taken as 1° F. for every 53 feet in depth. Some authors maintain that this rate is excessive, and that the rate of 1° F. for every 80 feet is the true average. But many of the flowing wells in Australia show the rate of 1° F. for every 22 feet. This high temperature indicates that the water has probably come from a much greater depth than that of the water-bearing layer. It is, therefore, more likely to be plutonic than meteoric."

It may be remarked that observations in regard to the rate of increase of temperature with depth, owing to the internal heat of the earth, have not shown very consistent results in other parts of the world, as will be seen by the accompanying table:—

OBSERVED Temperatures in Excavations.

Locality.	Depth in feet of Excavation.	Depth in feet for increase of 1° F.
Bootle Waterworks (Liverpool)	1,392	130
Przibram Mines (Bohemia)	1,900	126
St. Gothard Tunnel	5,578	82
Mont Cenis Tunnel	5,280	79
East Manchester Coal-field	2,790	77
Paris Artesian Wells	1,312	56·7
London Artesian Wells (Kentish Town)	1,100	55
Yakoutsk frozen ground (Siberia)	540	52
Sperenberg Bore (Berlin)	3,492	51·5
St. Petersburg Well (Russia)	656	44
Carrickfergus, shaft of salt mine	770	43
,, ,, ,,	570	40
Slitt Mine, Weardale, Northumberland	660	34
Fort Randall Artesian Bore, Dakota, U.S.A.	576	17·5

In view of the extremely wide differences in the temperature gradient, as shown by these figures, it would surely be very illogical to contend that, because some Australian artesian bores give higher rates of increase than the *average* of those results quoted above, the water must be plutonic and not meteoric.

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* The Dead Heart of Australia, pp. 315–317.

In the Dakota artesian basin the temperatures of the waters from flowing wells show even more remarkable anomalies than those in Australia. Darton[*] mentions that at the Fort Randall well, in the Missouri Valley, the rate of increase of temperature is 1° for each 17½ feet, while at the Chamberlin well the rate is 1° for each 21½ feet, and at the Pierre well 1° for each 24½ feet. In other parts of the basin the rate varies down to 1° for each 41 feet. Darton also draws attention to the fact that the area within which the higher temperatures are met with corresponds with a deep valley in the submerged "bed-rock surface," while the area which is characterised by cooler conditions is coincident with an underground ridge of quartzite, which, in fact, outcrops at the surface in places. There are indications at the north side of the buried ridge that the quartzite is underlain by granite.[†]

It seems possible that these variations in the temperature gradient may be due to the irregularities in the submerged bed-rock surface, and to the differences between the conductivities and thermal capacities of the bed-rock and of the overlying water-bearing series respectively, though it is noteworthy that the author of the paper quoted considers that all the explanations which have yet been suggested, including that of "different ratios of conductivity" are unsatisfactory.

The abnormally high temperatures referred to by Gregory as occurring in some of the Australian bores may also be possibly due to the bores having been put down in proximity, in some cases, to centres of expiring volcanic activity. The Triassic rocks along the coast of New South Wales were intruded, during Tertiary times, by many dolerite dykes, and there is evidence all over the eastern States that volcanic activity was very wide-spread during that period. It is therefore only reasonable to suppose that the porous Triassic sandstones which form the base of the artesian basin have also been intersected by many dolerite dykes, which do not appear at the present surface because they are older than the Post-Tertiary deposits of which it is formed. As a matter of fact specimens of dolerite have been brought up with the drillings from some of the bores.

It is admitted that it is difficult to find a perfectly satisfactory explanation of these differences in temperature, and this is hardly to be wondered at, seeing that the great depth of the bores prevents us from ascertaining the exact conditions which prevail at their extremities. It may be as well to repeat therefore that the foregoing suggestions are merely put forward as *possible* explanations. In any case it is difficult to see that these anomalous temperatures are any proof of the truth of Professor Gregory's contention, viz., that the water is of plutonic origin; for, if it were, we would expect it to reach the surface with a temperature of at least 212°, whereas in no single instance does it do so. The highest temperature recorded for any artesian well in Australia is 202° at Elderslie bore, 4,523 feet deep, and situated about 40 miles west of Winton in Queensland.

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[*] N. H. Darton, Geothermal data from deep artesian wells in the Dakotas, Quart. Journ. Sci., v, 1898, pp. 161-168.

[†] N. H. Darton, Ann. Rept. U. S. Geol. Survey, 1895-6, XVII, Pt. II, p. 673.

Anomalies in Pressure.—In considering anomalies in regard to the observed pressure of Australian artesian bore waters, Professor Gregory makes a critical analysis of the data published by the officials of Queensland, New South Wales, and South Australia. As a result, he considers that the irregularities in regard to the distribution of water pressure are too great to be explained by variations in the texture and thickness of the porous water-bearing beds, and he advances this as a further argument against the acceptance of the hydrostatic pressure theory. It is not considered that any useful purpose would be served by closely following the details of Gregory's criticism so far as it relates to the location of isopotential lines. It may be stated at once that the work done in determining the position of isopotentials, independently, in the three States, is patchy and very incomplete, and to deduce anything definite from it in its present stage would be like attempting to fit together a toy puzzle of which half the pieces are missing. Moreover it is quite possible that errors may have occurred in some of the determinations which would account for the apparent crossing of some of the isopotential lines referred to by Gregory. It is very much to the credit of the hydraulic engineers of the three States that they have accomplished so much in the face of great difficulties, but Mr. J. B. Henderson informs me that most of the levels of the Queensland bores have been taken by aneroid observation, and although Mr. J. A. Griffiths (Mr. Henderson's assistant) performed this work with the greatest care, it is impossible that the same accuracy could have been obtained as if the dumpy level had been employed. Until, therefore, the work has been checked, and carried much nearer to completion, it would be futile to attempt to explain the inconsistencies which appear to exist in the published maps. It may be stated that similar anomalies in regard to pressure have been noticed in the artesian wells of the Dakota basin, and they have not been definitely accounted for, though several possible explanations have been advanced.[*]

It is understood that the isopotential work in South Australia has been performed with the aid of the spirit level, as has that in New South Wales, and the fact (recorded by Professor Gregory)[†] that Mr. J. W. Jones successfully predicted the height to which the water would rise in some localities, appears to be incapable of explanation except on the assumption that the flowing wells are caused by hydraulic pressure.

One statement of Professor Gregory's in regard to the subject of isopotentials requires to be amended. He says[‡] that in New South Wales there is no evidence of regular decrease of pressure towards the west; but a glance at the map published by Mr. Allan* will show that the hydraulic grade has a fairly uniform fall to the west and north-west. It may be added that the discrepancies noticed in the pressures of adjacent wells may be due to their deriving their water from different porous beds. In connection with this question Mr. Allan† writes:—

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[*] N. H. Darton, Preliminary Report on Artesian Waters of a Portion of the Dakotas. Ann. Rept. U.S. Geol. Survey, 1895–6, xvii, pp. 668–9.

[†] Dead Heart of Australia, p. 293.

[‡] *Ibid.*, p. 311.

> "It must however be remembered that, whilst in the case of Government bores the records have been well kept and the different flows determined until bed-rock has been obtained, yet in the case of private bores such data are not available, and there is the consequent possibility of the recorded pressure in a private bore being for a flow in a much higher sheet of water-bearing strata than that noted in connection with an adjacent bore. This necessitates the isopotential lines being taken as tentative."

Salinity of Artesian Waters.—Amongst Professor J. W. Gregory's objections to the theory of hydrostatic pressure, as applied to the Australian artesian basin some of those upon which he lays most stress are based upon the chemical composition of the water. He states—(1) that the water does not increase in salinity with sufficient regularity as it flows from east to west, or in other words from its source to the most distant wells; (2) that the dissolved constituents vary irregularly in nature as well as in amount in the wells of the central basin; (3) that the presence of the carbonates of soda and potash in the majority of the well waters, of lithium carbonate in the Helidon wells, and of zinc in "the well of Toowoomba" are evidence in favour of the plutonic origin of the water.

With regard to objections (1) and (2) it is surprising that any geologist should expect that a stratified deposit could extend for a distance of 600 miles, or more, without showing marked variations in what may be termed its accidental constituents, or that the salinity of the water which percolates through it for that distance should increase, from the intake to the farthest wells, by regular arithmetical progression. It is well known amonst the pastoralists of the Western Plains that shallow wells, which yield fresh water, are commonly found in proximity to others which yield salt water, and there is no indication on the surface as to the character of the water which may be met with at any spot. There is therefore nothing remarkable in the fact that the deeper (artesian) wells contain water of variable salinity, both as regards quality and quantity. On the contrary it is considered that the increase of salinity from east to west (as illustrated by the table on page 314 of "The Dead Heart of Australia"), is quite as marked as could be expected, and, as will be shown later, the *average* salinity of the South Australian wells is distinctly higher than that of the wells in the eastern States.

Professor Gregory refers to the Maria Creek bore, to the east of the basin, as being one of the richest in solid constituents,‡ and as forming, on that account, evidence in favour of his contention that the salinity of the artesian wells does not increase from east to west. But here he falls into an error through want of personal knowledge of localities. The Maria Creek bore (Queensland) is entirely outside of the artesian basin; in fact it is at least 65 miles to the eastward of the nearest outcrop of the intake beds. It is in an area of Permo-Carboniferous rocks, and was put down in search of coal. The chemical composition of its waters has therefore no bearing upon the subject under consideration. Reference is also made to the excessive salinity (1,250 grains of solids per gallon) of the Boort well near Cunnamulla; but this is a shallow well which was put down in the shales and limestones of the Rolling Downs formation, and it is therefore several thousand feet above the porous sandstones of the artesian basin.

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* Percy Allan, The Drought Antidote for the North-west, New South Wales, 1906, pp. 44, 45.
† *Ibid*, p. 45.
‡ Dead Heart of Australia, p. 312.

Alkaline Carbonates.—It is difficult to understand why the hydrostatic pressure theory should be condemned on account of the presence of alkaline carbonates in the water, and it cannot be admitted for one moment that the presence of those substances is any proof of plutonic origin. In the first place there is nothing unusual in artesian water containing alkaline carbonates. Thus, some of the artesian well waters of Iowa contain these salts.[*] The artesian waters of Texas contain much alkaline carbonates; the average solid contents of these waters from six localities, from Fort Worth southwards, are given as follow[†]:—

Chlorides (chiefly Na)	... ...	12,707 grains per gallon
Carbonates ,,	... ...	20,750 ,, ,,
Sulphates ,,	... ...	21,464 ,, ,,
		54,921

These water-bearing beds, the "Trinity Sands," are at the base of the Lower Cretaceous system. The artesian waters of the Cretaceous basin of Alabama also contain considerable quantities of alkaline carbonates.[‡]

But in any case it is unnecessary to go to any plutonic depths to discover the source of the alkaline carbonates in the Australian basin, for it will be revealed by a slight examination of the porous beds where they outcrop at the surface. The Triassic sandstones have all the appearance of having been derived from the disintegration of granites. They consist of grains of quartz with a very felspathic looking cementing material. It is a fair assumption that the granites contained soda- and potash-felspars, the decomposition of which would yield just such a clay, and, as a matter of fact, analyses recently made in the Geological Survey laboratory of two samples of the porous sandstone proved that this rock contains an appreciable proportion of alkalies. The results were as follow:—

Sample from near Dubbo, N.S. Wales	Potash 1·34% Soda 0·55%
Sample from near Texas on the Queensland-New South Wales Boundary.	Potash 2·06% Soda 0·45%

The two localities are about 300 miles apart.

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[*] Iowa Geological Survey, vi, 1897, p. 186-7.

[†] Ann. Rept. U. S. Geol. Survey, 1899-1900, xxi, Pt. 7, p. 448.

[‡] E. A. Smith, The Underground Water Resources of Alabama, Geol. Survey Alabama, 1907, pp. 361, 362.

The soda and potash in the artesian water are thus easily accounted for, while the rain which falls upon the catchment area doubtless contains the usual proportion of carbonic acid, and an additional source would be provided by the oxidation of organic matter.

Lithium Carbonate.—With regard to the alleged presence of lithium carbonate in the Helidon wells it may be observed that these wells are outside the artesian basin, as the sketch-section (Pl. III) will show, and therefore the occurrence in them of lithium or any other substance would have no significance so far as the subject under discussion is concerned. As a matter of fact, however, Mr. Henderson, the Queensland Government Analyst, informs me that he has examined three samples of Helidon water for lithium and has failed to find a trace of it even with the aid of the spectroscope.

Zinc in Toowoomba Water.—The reputed presence of 2½ grains of zinc per gallon in "the well of Toowoomba" can also be shown to be a matter of no consequence, so far as the origin of the artesian water is concerned. The town of Toowoomba is built, at an altitude of about 2,000 feet, upon a flow of basalt which forms the surface of the well-known Darling Downs. The basalt overlies the Triassic sandstones, which dip to the westward, and which here constitute the intake beds of the artesian basin. The basalt is very vesicular in character, and is found to contain a plentiful supply of water, which is doubtless derived from rainfall. As a consequence of this a great number of wells have been sunk in the neighbourhood of Toowoomba and over the Downs generally, the average depth at which the water is struck being about 100 feet from the surface. It will be understood then that this water-supply occurs at an altitude of nearly 2,000 feet above sea-level, and that it lies above the outcrop of the porous beds of the artesian basin. If zinc really occurred in this water, therefore, it could by no possibility have been derived from the artesian beds. But it is extremely doubtful whether there is any zinc in the Toowoomba well water in its natural state. Each of the wells is fitted with a

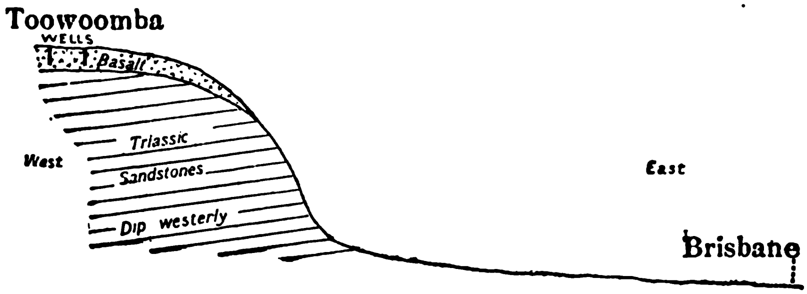

Fig. 4.—Wells in basalt at Toowoomba.

pump which raises the water into a galvanised-iron tank alongside, and in most cases the pipe through which the water is conveyed to the tank is also constructed of galvanised iron. Mr. Henderson, the Government Analyst of Queensland, has forwarded me a communication from the Town Clerk of Toowoomba, enclosing extracts from a press copy of a letter, dated 18th August, 1897, forwarding a number of samples of water for analysis; referring to sample No. 3, from the Government Pound Paddock, (which is the one in which the zinc was found); the extract reads, "*This bore has a galvanised tube left in since completion six weeks ago, and has not been baled out since.*" The presence of zinc in the water can therefore be easily understood.

Salinity of Artesian Water as compared with Mine Water.—While the *quality* of the saline constituents of the artesian water cannot be taken as proof of its plutonic origin, the *quantity* of salts in solution must assuredly be regarded as an argument strongly opposed to Professor Gregory's contention. It has already been stated that the porous water-bearing sandstones of the Triassic Coal Measures consist of quartz sand with a rather felspathic cementing material, and it is therefore to be expected that water percolating through these beds would not carry such a high percentage of mineral salts in solution as if it had been in contact with slates, shales, or limestones. A comparison of the analyses of the artesian waters with those of mine waters fully bears out this conclusion, as the following figures will show. All the available analyses of water from the porous beds of the artesian basin in Queensland, New South Wales, and South Australia have been taken for the purpose of this comparison.

Waters from Porous Beds of Artesian Basin.

143 samples from Queensland give an average salinity of 47·94 grains per gallon.

177 samples from New South Wales give an average salinity of 56·35 grains per gallon.

14 samples from South Australia give an average salinity of 141·62 grains per gallon.

The average salinity of the 334 samples from all three States is 56·32 grains per gallon.

All the available analyses of Australian *Mine Waters* have also been collated. There are thirty-five of these, viz., two from Victoria, eleven from New South Wales, and twenty-two from West Australia, and their average salinity is 1674·48 grains per gallon. These waters were all taken from comparatively shallow depths, and their high salinity, as compared with that of the artesian waters, is evidence of their having been in contact with more highly mineralised rocks. If now we consider the conditions under which *plutonic waters* would occur, having their source at great depths, and percolating, under extremely high temperature and pressure, through calcareous, ferruginous, and felspathic rocks, it is obvious that their salinity would be far in excess, not only of the artesian waters, but of the mine waters referred to above; it might, in fact, be expected to amount to many thousands of grains per gallon, for the waters, under such peculiar conditions of heat and pressure, would become supersaturated with salts.

In view of the foregoing considerations, it is contended that the chemical composition of the Australian artesian waters, so far from indicating a plutonic origin, constitutes very strong evidence against it, and is, furthermore, quite consistent with the assumption that they have been derived from rainfall.

It will also be noted that the average salinity of the South Australian waters is much higher than that of the waters from the eastern States, a fact which is in accordance with the supposition that the water travels from the Great Dividing Range westwards towards Lake Eyre.

Gas Pressure.—In dealing generally with the subject of flowing wells, Professor Gregory separates those whose waters are charged with gas from those which are not so characterised; and this is a distinction which no one is likely to cavil at, since the cause of their ascent is clearly different in the two cases. He makes the following statement, however[*]:—

> Some of the flowing wells in the artesian area of New South Wales are classed by Mr. Pittman as "mineral waters." Thus the water known as Zetz Spa, found in the Talbragar Valley, north-east of Dubbo, comes up through a bore-hole; and there is no obvious reason why it should be placed in a different category from some of the artesian waters. It contains 224 grains of solids per gallon, including 183 grains of bicarbonate of soda.

A reference to the work alluded to[†] will show that my reason for classing this as a mineral water was the very obvious one that it is heavily charged with carbonic acid gas. Moreover, this bore, although situated within the extreme boundaries of the artesian basin, was put down in an inlier of Permo-Carboniferous rocks in search of coal.[‡] Singularly enough, in a subsequent paragraph of his book (page 317) Professor Gregory states that the water from this well is "*charged with carbonic acid.*"

It has already been stated that the Helidon wells (Queensland), the waters of which are also charged with carbonic acid gas, are outside the artesian basin, and it is probable that they also penetrate Permo-Carboniferous rocks underneath the Triassic. The Maria Creek bore (Queensland), from which there were emissions of marsh gas, and from which the flow of water was intermittent, and finally ceased, is undoubtedly in the Permo-Carboniferous rocks, and well outside the artesian basin. Another bore from which both marsh gas and petroleum were emitted is situated at Roma, in Queensland, and here again it seems probable that the gas and oil, which are not characteristic of the ordinary artesian wells, may emanate from underlying Permo-Carboniferous rocks penetrated by the bore. In a bore which was put down at Grafton (New South Wales) with the object of testing the Triassic sandstones of the Clarence River basin for water, only a small supply, which rose level with the mouth of the bore, was met with between forty and one hundred feet from the surface. The bore was continued to a total depth of three thousand seven hundred feet, and at three thousand one hundred feet a considerable volume of marsh gas was given off, and burned at the mouth of the well. Marine beds of the Permo-Carboniferous system are known to occur at Drake, to the north-west of Grafton, and it seems probable that the fresh-water coal-bearing beds of that system also underlie the Clarence basin, and that the gas which was met with in the Grafton bore emanated from them.

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[*] Dead Heart of Australia, pp. 315, 316.

[†] E. F. Pittman, The Mineral Resources of N. S. Wales, 1901, pp. 448-9.

[‡] W. Anderson, Ann. Rept. Dept. Mines, N. S. Wales, for 1898, p. 184.

With regard to the presence of sulphuretted hydrogen in artesian water, Mr. Hamlet, Government Analyst of New South Wales, stated (in a report to the Works Department, dated 30th January, 1901) that he had failed to detect gas at three bores visited by him. The characteristic odour, however, is distinctly noticeable at most of the bores, and the occurrence of sulphuretted hydrogen is doubtless due to the reducing action of decomposing organic matter upon sulphates, the latter being probably derived from the oxidation of pyrites, which usually occurs in the vicinity of intrusive dykes.

Tidal Wells.—While no satisfactory explanation can as yet be offered to account for the rise and fall of the water in the Urisino Well (New South Wales), the suggestion made by Gregory,* that the phenomenon may be due to the escape of carbonic acid gas, cannot be endorsed. There is no visible evolution of gas, the surface of the water being apparently quiescent; moreover, the writer stood for a considerable time on a staging which had been erected inside the mouth of the well, and the fact that the air there was perfectly innocuous is proof that there was no accumulation of carbon dioxide. The suggestion as to geyser action would appear to be equally untenable. It may be added that the Professor is mistaken in supposing that more than one tidal well is known in New South Wales. The Ninety-one Mile is a Government bore, situated about six or seven miles from the Urisino bore, but it does not exhibit variations in the height of the water as the latter does. It is probable that the two names have been confused on account of the Urisino being so close to the Ninety-one Mile.

Oxton Downs Bore—Water in Granite?—The artesian bore at Oxton Downs (Queensland) is said to have obtained its supply from granite, and Professor Gregory regards this is as *certain evidence that the water is plutonic.*† If it could be proved that this water was actually derived from granite, the occurrence would be unique, for although very many bores have bottomed in that rock, there is no other instance on record in which a flow was obtained after the granite was penetrated. For this reason it might have been expected that the statement as to the source of the Oxton Downs water would be received with very great caution, until it had been placed beyond all doubt, or at least until other similar occurrences had been met with. This bore is a private one, and was put down under the superintendence of Mr. Hugh Moor, at that time (January, 1891) manager of the Manfred Downs Station. The Queensland records show that the bore was not visited by a Government official until nearly six years after its completion. It was then inspected by Mr. J. A. Griffiths, who was in charge of the Hydraulic Survey of the Northern Division of Queensland, under Mr. J. B. Henderson, Hydraulic Engineer for the State. Mr. Griffiths' report, which is dated 30th November, 1896, states:—

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* Dead Heart of Australia, p. 330.
† *Ibid.*, p. 317.

> A small flow was met with in the sandstone at 700 feet, a little more at 900 feet, in the granite, and the main flow, estimated at 120,000 gallons per diem, issued from a fault or crack in the granite at 1,060 feet.

As Mr. Griffiths obtained this information from Mr. Hugh Moor, I wrote to that gentlemen and asked him what evidence he had of the crack or fault. He has been courteous enough to send the following reply:—

> The only evidence I can give you as to the water being struck there in a fault is from the borer's description, which, as far as I can remember, was as follows. I know they had been drilling for some weeks on granite, making very slow progress, when all at once the drill dropped 6 or 8 feet, according to their report, at a depth, if I remember right, of about 1,020 feet. Water shortly began to increase in flow after this drop, and they went on a few feet more, I forget how many, in fairly soft drilling, and then came on hard again, when I knocked them off. During the time they were following this crack (as we called it) down, a lot of flaky granite came up in the flow, very thin, mostly oval, and about as big as a threepenny piece. A lot of these drillings were saved at the time, and were left on the station when I left there. I think there is no doubt this was a crack or fault, but how wide or deep, or in what direction trending, I could not tell you. I am certain the top rock was granite, as I believe some of the drillings were submitted to yourself at the time, and you pronounced them "bed-rock."

There does not appear to be very much evidence here upon which to base an assertion that the water is of plutonic origin. It is clear that the main water-bearing sandstone beds must be in proximity to the bottom of the bore, for (according to Mr. Griffiths' report) some sandstone was penetrated and a small flow obtained from it. It seems highly probable, therefore, that the crack or fissure in the granite is in direct communication with a lower stratum of the porous beds, and that the water was really derived from the latter.

Outlet for Artesian Basin.—In connection with the supposed existence of an outlet for the subterranean waters at the Gulf of Carpentaria, Professor Gregory gives a section of the artesian basin from the Gulf to Charleville, and he shows, as a marked feature of this section, a rock barrier or submerged range of granite in the vicinity of Manfred Downs. In speaking with reference to this he says*:—

> The section on page 306 shows that an outlet to the Gulf of Carpentaria is of no use to the deep basin beneath the Lake Eyre country, for its waters are far below the level of the outlet into that gulf. Hence, so far as concerns the flowing wells of the south-western part of the central artesian basin, the water must be stagnant.

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* Dead Heart of Australia, p. 299.

It is difficult to understand why the Professor arrives at this conclusion. The water must circulate through the lowest parts of the basin, so long as it has sufficient head. The fact that "*that part of the basin beneath Lake Eyre is far below the level of the outlet into the Gulf of Carpentaria*" is of no consequence, so long as the *source* of the water, or, in other words, the *outcrop of the porous beds*, is at a sufficient altitude above the submerged granite barrier at Manfred Downs. If Gregory had continued his section from Charleville on to Toowoomba, as has been done in the sketch (Pl. III), the fact that the porous beds there have an outcrop at least one thousand feet higher than Charleville would have been apparent. It may be added that the water beneath Lake Eyre is not stagnant, for the same reason that the water at F, in figure 5 (which is reproduced from "The Dead Heart of Australia"), would not be stagnant, but would flow over the barrier at F, so long as its source is at a higher level.

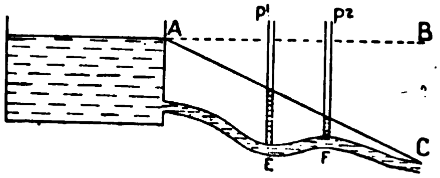

FIG. 5.

An inspection of the country between Brisbane and Toowoomba would probably convince Professor Gregory that the artesian basin has no outlet in the neighbourhood of the first-named place. It will be seen in the section (Pl. III) that Toowoomba lies at an elevation of about two thousand feet above sea-level, that the Triassic sandstones here have a *westerly* dip, and that immediately east of Toowoomba there is a steep escarpment leading down to the coastal plain on which Brisbane is situated. A considerable outcrop of Palæozoic rocks (regarded by Dr. Jack as Lower Carboniferous) occurs near Brisbane, and it is more than possible that an area of Permo-Carboniferous sediments may underlie the Triassic sandstones near the mountains. A bore at Laidley, fifty one miles west of Brisbane, yielded a flow of one thousand six hundred gallons per day of very saline water at a depth of two thousand five hundred and twelve feet. Another bore at the Racecourse, four miles from Brisbane, reached a depth of one thousand seven hundred and eighty-one feet, and yielded eight thousand two hundred and twenty-eight gallons per day. Both these flows are believed to be of local origin.

Darling River Rainfall and Run-off.—The late Mr. H. C. Russell, Government Astronomer of New South Wales, first drew attention to the fact that only a very small percentage (estimated by him at 1·46 per cent.) of the rainfall on the Darling catchment area actually flowed past Bourke through the channel of the river, whereas he assumed that in the case of the Murray the run-off of the river amounted to 25 per cent. of the rainfall. He concluded, therefore, that a large proportion of the Darling rainfall must pass underground. Commenting on this, Professor Gregory says,*—

> The view that the ascent of the water in the flowing wells is due to the pressure of water in the Queensland hills does not seem to me to be any longer tenable. The responsibility for this view rests with the meteorologists. It was originally based on a 75 per cent. under-estimate of the discharge of the Darling River, a 300 per cent. over-estimate of the discharge of the Murray, and a large exaggeration of the estimated proportion of the rain discharged by rivers in general.

He also makes the following statement† :—

> The Murray River and the Darling both discharge about the same proportions of the water that falls upon their basins ; and, considering the climate and the nature of the country that they drain, the amount is not unduly low.

If these emphatic statements could be proved to be correct, it must be admitted that the evidence in favour of the meteoric origin of the artesian water would be seriously discounted, but indeed they are very far from being correct. Mr. Russell's original estimates of the run-off of the Darling and Murray Rivers were necessarily based upon very imperfect data ; since then, however, much more systematic gaugings of these rivers have been carried out by the engineers of the Public Works Department, and, consequently, it is now possible to obtain fairly accurate data.

Mr. R. T. McKay, Assistant Engineer of the Works Department, has dealt at considerable length with this question in a paper read before the Royal Society of New South Wales.‡ The following tables have been copied from his paper :—

TABLE of Rainfall and Run-off of the Darling River at Wilcannia.—Catchment area, 235,000 square miles.

Year.	Annual discharge of the Darling at Wilcannia in millions of cubic feet.	Mean discharge in cusecs.	Second feet per square mile.	Mean rainfall in inches over catchment.	Run-off in inches over catchment.	Percentage discharged.
1894	253,644	8,043	0·034	26·81	0·464	1·73
1895	60,234	1,910	0·008	19·53	0·110	0·56
1896	87,733	2,782	0·012	21·14	0·161	0·76
1897	70,199	2,226	0·009	18·94	0·128	0·67
1898	57,049	1,809	0·008	15·87	0·104	0·66
1899	27,783	881	0·004	16·04	0·051	0·31
1900	69,474	2,203	0·009	16·33	0·127	0·77
1901	32,167	1,020	0·004	15·71	0·059	0·37
1902	710	22	0·0001	11·22	0·001	0·01

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* Dead Heart of Australia, p. 336.

† *Ibid.*, p. 297.

‡ R. T. McKay, Rainfall and discharge of the Murray River and its tributaries. Journ. R. Soc. N. S. Wales, 1906, XL. pp. xlvi-lxxxii,

TABLE showing Rainfall and Run-off of Murray River at Morgan.—Catchment area, 408,000 square miles.

Year.	Annual discharge in millions of cubic feet.	Annual discharge in acre feet.	Mean annual discharge in second feet.	Run-off.		Rainfall in inches over catchment.	Percentage discharged.
				In second feet per square mile.	In inches over catchment.		
1895	509,951	11,706,945	16,170	0·039	0·54	17·35	3·12
1896	297,939	6,839,786	9,448	0·023	0·32	18·21	1·75
1897	277,548	6,371,669	8,801	0·022	0·29	16·46	1·76
1898	281,787	6,468,984	8,935	0·022	0·30	15·28	1·96
1899	274,619	6,304,428	8,708	0·021	0·29	15·23	1·90
1900	424,271	9,739,989	13,454	0·033	0·45	16·64	2·70
1901	242,321	5,562,963	7,684	0·019	0·26	14·68	1·77
1902	93,274	2,141,291	2,958	0·007	0·10	10·64	0·94
Means	300,214	6,892,007	9,519	0·023	0·32	15·56	2·00

Taking the mean of the figures in the last columns of the two tables, it will be found that the percentage ratio of the run-off to rainfall of the Murray at Morgan is about three times as great as that of the Darling at Wilcannia. But this comparison is unsatisfactory, because, Morgan being below the junction of the Darling with the Murray, the result obtained there will include the run-off of the Darling; and again, Wilcannia being about two hundred and thirty miles above the junction, the percentage of run-off there is higher than it would be at Wentworth, because the Darling receives no tributaries between the two towns, and this stretch of the river is subject to great loss from evaporation. I therefore asked Mr. McKay whether he could give a more exact comparison between the two rivers. In reply, he says* :—

In accordance with your request, I have continued the investigations of rainfall and run-off of the Murray River and its tributaries, and am now able to make a comparison of the Murray and Darling catchments at the junction of the two rivers. It has been asserted that the percentage of run-off of the Darling is about equal to that of the Murray, but such a statement must have been made without a knowledge of the various watersheds.

Dealing with the period 1895–1903, inclusive, of the Darling catchment at Wentworth, and the Murray catchment at Wentworth, the following results are obtained :—

1895	Murray percentage of run-off is	19	times greater than Darling.
1896	,, ,, ,,	7	,, ,, ,,
1897	,, ,, ,,	9	,, ,, ,,
1898	,, ,, ,,	9	,, ,, ,,
1899	,, ,, ,,	21	,, ,, ,,
1900	,, ,, ,,	11	,, ,, ,,
1901	,, ,, ,,	17	,, ,, ,,
1902	,, ,, ,,	180	,, ,, ,,
1903	,, ,, ,,	4	,, ,, ,,

Taking each catchment as a whole, it will be seen for the nine years in question, that every square mile of Murray watershed discharged thirty-one times more rainfall than a similar area of Darling watershed. In the above the abnormal drought year 1902 is included, and perhaps it might be regarded as unfair to include such a year in comparative records of run-off. If 1902 be excluded for the period under review, we find that the proportion of rainfall discharged from the Murray catchment is twelve times greater than that of the Darling. The volume discharged by each river must not be confused with the percentage of run-off, as the Murray at Wentworth does not discharge anything like twelve times the volume sent down the Darling channel. This, of course, is obvious, as the Murray watershed is so much smaller than the Darling.

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* Personal communication dated 29th August, 1907.

The information on which the above calculations are based, is as complete and reliable as it is possible to attain with the available data of river discharges and rainfall observation, and may be accepted as within the reasonable limits of accuracy.

It is evident from Mr. McKay's very interesting results, that, although the late Mr. Russell's figures were based upon very imperfect data, they were not, after all, for purposes of comparison, so very far from the truth.

It may therefore be regarded as a fact that the ratio of run-off to rainfall in the case of the Murray is very much higher than it is in the case of the Darling, and this is undoubtedly due to marked differences in the geology of the two catchment areas. The tributaries of the Murray (above Wentworth) all flow over granitic rocks, or dense Palæozoic sediments; on the other hand, all the tributaries of the Darling, in their upper reaches, cross the porous intake beds of the artesian basin, and thus a large proportion of the rainfall finds its way underground, and feeds the flowing wells. These tributaries of the Darling are the Bogan, Macquarie, Castlereagh, Namoi, Gwydir, McIntyre, Dumaresq, Culgoa, and Warrego.

Evaporation.—Professor Gregory discusses at considerable length the question of evaporation, and endeavours to show that most of the Darling rainfall is lost in that way rather than by percolation underground. He states* that evaporation would get rid of more rain than ever falls in Central Australia. No one would think of questioning the truth of this statement, but it has little or no bearing upon the subject under discussion. The water does not enter the porous beds in *Central Australia*, but on the flanks of the Dividing Range, at high altitudes, where the rainfall is much greater, and the evaporation much less than it is in the central plains.

Internal Heat of the Earth.—The objections to the hydrostatic pressure theory having been discussed and answered, Professor Gregory's suggestions as to the cause of the ascent of the water in the flowing wells may now be briefly considered. They are that it is due to the internal heat of the earth, and to the effects of rock pressure. With regard to the first it may be stated that if the earth's internal heat were sufficient to cause the water to rise above the surface in bores, it would, before the bores were put down, have forced the water back along the porous beds, with the result that it would have overflowed at the surface; in other words, the porous beds would never have become saturated with water. Another objection is that the water is not hot enough to be accounted for in this way, the hottest water flowing from an artesian bore being ten degrees below boiling point.

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* Dead Heart of Australia, p. 325.

Rock Pressure.—The second suggestion is that the water is forced to the surface by the pressure of an overlying sheet of impermeable rock. On this subject Gregory writes* :—

> Attention was first called to the importance of rock pressure in reference to flowing wells by R. Hay. . . . See *e.g.* F. B. Gipps, Journ. R. Geogr. Soc. Austral. (New South Wales Branch), Vol. VI; 1896, p. 4.

Several objections to the theory that flowing wells are due to rock pressure suggest themselves. In the first place, the effective pressure at any given point in the porous beds will be less than that due to the total weight of the overlying rocks because on account of the cohesion of these rocks, and the continuity or lateral extension of the beds, they act more or less like the arch or girder of a bridge. The weight of the overburden at any point would not be completely felt until a depth had been reached where the rocks were in a plastic state.

If a single brick be knocked out of the lowest course of a high wall, the weight of the wall will not close up the space left by the brick, because of the cohesion between the bricks and mortar, and because, in the different courses, the bricks are laid "breaking joint." If the bricks were laid accurately and vertically over one another, and without any mortar, the space caused by the withdrawal of one would be immediately filled by the fall of all the overlying bricks.

Then again, if the pressure on a porous bed be sufficient to squeeze out the water when the bed is intersected by a bore, it is evident that the same pressure would have been sufficient to prevent the water from filling the porous bed in the first instance.

A third argument against the rock pressure theory is that even if it were possible for a porous bed to be first filled with water, and subsequently subjected to the rock pressure suggested by Professor Gregory, the effect would be that the water would return to the surface along the intake area ; for the pressure, being vertically downwards, would have a tendency to squeeze the water laterally along the porous bed until it escaped at the surface. The ultimate result of the pressure on the porous bed would be to render it dense and indurated, and it would thus lose its capacity for absorbing water.

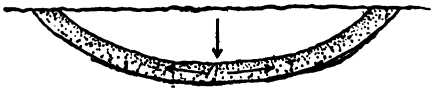

FIG. 6.

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* Dead Heart of Australia, p. 289.

The theory of rock pressure as a cause of flowing wells was advanced many years before it received the advocacy of Mr. Robert Hay. It has been ably dealt with by Mr. W. H. Norton, an American geologist of high repute, from whose writings* the following extract may be quoted:—

> A rival theory to the hydrostatic theory was that of "rock pressure," which assumed that the water of artesian wells is squeezed out of the aquifer by the enormous pressure of the superincumbent rocks. This was answered by Arago early in the nineteenth century, but lingering in the popular mind, and again put forward of late years as an explanation of the flows of petroleum and natural gas, it has once more been laid by Leslie (Ann. Rept. Penna. Geol. Sur., 1885), and by Orton (Geol. Sur. Ohio. Econ, Vol. VI). Recently it has been revived, as at least a subordinate and occasional factor in artesian flows, by Professor Robert Hay.
>
> Assuming a specific gravity of three times that of water for the strata of a region to the depth of 600 feet, he states that at that depth the pressure of the superincumbent rocks amounts to fifty-two atmospheres, and that if a water-bearing stratum at that depth be pierced by the drill, we should then have the rock pressure of fifty-two atmospheres squeezing the water out of the rock pores, and granting sufficient plasticity in the rock, and a sufficient quantity of water, it must rise in the tube, which has only the pressure of one atmosphere upon it. A large bore to the well, and a small supply of water, would be against it reaching the surface. On the other hand, a bed-rock with mobile molecules at or near saturation under this enormous pressure must cause, in a narrow tube, a flowing well.
>
> No objection need be offered to the supposition that circumstances might occur in which, for a short time, rock pressure might produce a flow of water under certain assumed conditions. But such occurrences must be local and temporary, as is the flow from wells sometimes produced by earthquake shocks.
>
> Flow from rock pressure demands as its first condition that the rock of the water-bearing stratum has lost its cohesion. It must be plastic and mobile, crushed and comminuted; otherwise it exerts no more pressure on the water in its interstices than do the iron walls of a water-main on the water flowing within them. The walls of a high building exert great pressure on their foundations, but it would hardly be suggested that this "rock pressure" exerted upon the water pipes passing through or beneath these foundations, is the cause of the rise of water from them to the upper stories of the building. And not only must the rock of the water-bearing stratum be crushed and incoherent in order to transmit rock pressure to the water which it contains; that water must also have entered the stratum before the pressure was exerted upon the rock, or before the rock was in a condition of mobility so that it could transmit the pressure to the water. For a pressure sufficient to squeeze water out of a stratum is sufficient to prevent the entrance of water into that stratum. A flow from rock pressure is limited, therefore, to the amount of water which the water-bearing stratum will hold without replenishing.
>
> With the theory of rock pressure as a general cause of artesian flows, Arago's summary dealing is still sufficient (Sur les Puits Forés. Annuaire par le Bureau des Longitudes, pp. 228-229, Paris, 1835). He showed that there are three cases of rock pressure which may be considered. The rocks above, and including the upper impermeable stratum, either continue to yield until they come in contact with the lower impermeable stratum, or they stop in a position of equilibrium before that contact, or they experience an oscillatory movement. In the latter case the flow will be intermittent, and in the first two cases it will stop entirely, and thus in any case the theory is incompetent to account for the steady flow of artesian wells.

With the object of ascertaining whether Mr. Robert Hay's explanation (quoted by Professor Gregory), as to the cause of the Kansas flowing wells, had received official endorsement in the United States, I wrote to the Hon. Dr. Geo. Otis Smith, who courteously replied as follows, on the authority of Mr. M. L. Fuller:—

> Rock pressure as a cause of artesian flows has been advocated by several geologists besides Mr. Robert Hay, but has never been supported by any real evidence, and has never received

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* W. H. Norton, Artesian Wells of Iowa. Iowa Geol. Survey, VI, 1897, pp. 132, 133.

> official sanction, nor has it been generally accepted by careful private investigators. In fact, it should be regarded simply as a suggestion advanced to explain flows for which no other cause was known at the time.
>
> While no special investigations have been made of the Kansas wells, which you mention, they appear to differ in no way from many others developed in this country in the last few years. Flows from rocks which do not outcrop at the surface, and which are devoid of the usual basin structure, are not at all uncommon. In most instances the water reaches the lower water-bearing beds through vertical joints (or faults), the head of the water being determined by the ground water level at the point where the joints reach the surface. This is probably the case in the Kansas locality.

With regard to Professor Gregory's reference to a second (and Australian) advocate for the rock pressure theory, viz., Mr. F. B. Gipps, it may be stated that Mr. Gipps' views on this subject have not received the support of scientific men in Australia, but on the contrary have been severely criticised.*

In regard to the present reckless waste of the artesian water, and the question as to what extent the bores may be increased without overtaking the supply, Professor Gregory sounds a warning note which will appeal to most thinking men. The Australian artesian basin is the largest in the world, but there can be no doubt that even it must have its limits of productiveness. In the United States, some artesian basins have been exhausted to such an extent that the water ceased to rise above the surface. A notable instance is that of the basin from which the city of Denver draws its water supply. It was discovered in 1884, and within a few years about four hundred wells had been drilled, principally within the city; by the end of 1890 all but six of the city wells had to be pumped.

Professor Slichter, in commenting upon the fact, states that it is probably due to the low porosity and transmission power of the water-bearing strata rather than to the lack of rainfall upon the catchment area, and that the water withdrawn represents a supply stored in the rocks but not readily transported by the strata to meet the enormous draft. He adds—

> It must be kept well in mind that there is a limit to the amount of water that can be withdrawn from an artesian basin. There is no such thing as an inexhaustible supply in this connection. The amount of water available is limited on the one hand by the amount of rainfall upon the catchment area, and the facility with which the rainfall can obtain entrance to the porous stratum, and on the other hand by the capacity of the water-bearing rock to transmit the water over long distances, and diminution through leakage and seepage. These two limiting conditions are usually of sufficient magnitude to render the overdrawing of the supply a practical and present danger which should be constantly kept in mind." †

In Queensland and New South Wales increasing numbers of bores are giving diminished flows, and in some, for instance, the shallow bores on Kallara Station, in the Bourke district, the water has ceased to rise above the surface. In nearly all these cases the bores are situated near the margin of the basin, where one would expect the first sign of depletion to manifest itself. It is unfortunate that accurate records were not kept, from the first, of pressure and flow at all the bores, but in New South Wales, at any rate, this work is now being thoroughly carried out under the superintendence of Mr. L. A. B. Wade, Chief Engineer for Water Supply, etc. Isopotential lines are being systematically charted, the intake beds are being surveyed, and, when this is done, it is intended to take continuous gaugings of large streams where they enter and where they leave the porous rocks, with the object of determining the amount of water lost by percolation.

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* Journ. R. Soc. N. S. Wales, XXVII, 1893, pp. 431–443.

† C. S. Slichter, The Motions of Underground Waters, 1902. Water Supply and Irrigation Papers, U. S. Geol. Survey, No. 67, p. 94.

Conclusion.—Referring once more to the geological conditions which prevail in the great Australian artesian area, it may be repeated that there are inclined beds of porous sandstone, occupying a more or less basin-shaped hollow many hundreds of miles in extent; the floor of this hollow is formed of igneous rocks and altered sediments, which are practically impervious to water. A thick series of impermeable shales and clays covers the porous sandstones to a depth which, in places, reaches more than four thousand feet; and the exposed edges of the sandstone beds outcrop at high altitudes on the flanks of the Great Dividing Range, where they receive a considerable rainfall. These conditions are not disputed by Professor Gregory; on the contrary, he admits their existence* though he has not personally investigated them.

Everywhere within the limits of these widely-extending beds of porous sandstone (except where the impervious underlying rocks form elevations or ranges rising near to the surface) the boreholes which have intersected the porous beds have yielded large supplies of water under considerable pressure. On the other hand, no excavations which have been made outside the limits of the porous sandstone have yielded any water under pressure, and in a great many cases they have been dry. Moreover, our experience of the geological conditions enables us to indicate, with the utmost confidence, localities where it would be quite useless to search for artesian flows at any depth.

Does Professor Gregory wish us to believe that it is merely a coincidence that artesian water is thus confined to the porous sandstones, while outside the sandstone area the rocks are dry, or only contain an insignificant amount of moisture? If the rise of artesian water be caused by the earth's internal heat, assisted by rock pressure, why are those forces inoperative outside what is known as the artesian

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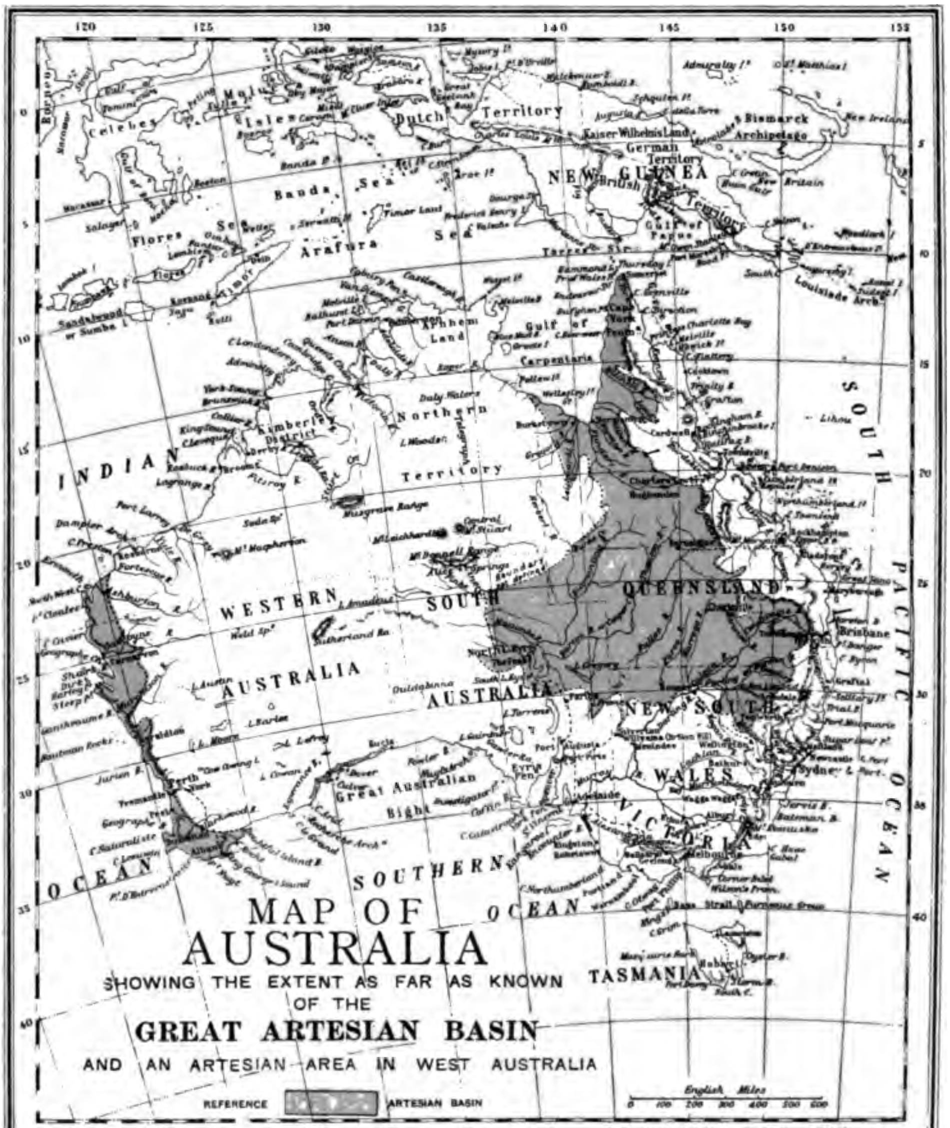
* The Dead Heart of Australia, p. 292.



MAP OF AUSTRALIA

SHOWING THE EXTENT AS FAR AS KNOWN OF THE

GREAT ARTESIAN BASIN

AND AN ARTESIAN AREA IN WEST AUSTRALIA

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basin, and what becomes of the supplies of water, which the Professor asserts are given off by cooling igneous rocks, in the neighbourhood of Tibooburra, Milparinka, Broken Hill, Cobar, Nymagee, Mount Hope, Girilambone, and a number of other well-known mineral-bearing localities which are but a comparatively short distance outside the boundaries of the artesian basin?

Until these questions have been satisfactorily answered, there would seem to be no reason for further considering the theory of temperature and rock pressure as an explanation of the rise of artesian water.

It may be confidently reaffirmed that the great Australian water-bearing basin is a true artesian area, that the water of the flowing wells had a meteoric and not a plutonic origin, and that hydraulic pressure is the chief cause of its ascent.

In conclusion, I venture to think that Professor Gregory's choice of a metaphor, in the title which he has given his book, is not altogether a happy one. When the heart ceases to beat, decay of all the other members of the body speedily follows. But if the heart of Australia, as symbolised by the desert country around Lake Eyre, be really dead, as suggested by the distinguished author, it is some consolation to know that there is still a fair amount of vitality in the head and limbs of our national body, as represented by the more fertile districts nearer to the coastline.

Postscript.—The rocks termed *Triassic* in this paper include the lower water-bearing sandstone (of fresh-water origin) of the great Australian artesian basin. In Queensland they are known as the *Trias-Jura*, and are there overlain in places by the *Blythesdale Braystone*, a porous marine sandstone, which forms the basal bed of the Lower Cretaceous system. The *Blythesdale Braystone* was probably a littoral deposit along the eastern margin of the Cretaceous sea, and it may not extend very far in the direction of its dip. It is not known to occur in the State of New South Wales, where the artesian water most certainly occurs in the older *Triassic* (or *Trias-Jura*) sandstones.

The *Trias-Jura* rocks of Queensland are characterised by the presence of the fossil plants *Tæniopteris Daintreei* and *Thinnfeldia*, and these fossils have also been recognised in New South Wales, both in the great artesian basin and in the Clarence River basin. In the Hawkesbury (Triassic) Sandstones of New South Wales, which are lithologically indistinguishable from the last named, *Tæniopteris Daintreei* has not, so far, been met with, although *Thinnfeldia* is plentiful. It is not quite certain, therefore, at present, whether the Hawkesbury Sandstones of New South Wales are identical with the Trias-Jura Sandstones of Queensland, or whether they occupy a lower geological horizon than the latter. About twenty miles north of Gulgong (New South Wales) there is a fresh water (lacustrine) deposit containing numerous fish remains, together with *Tæniopteris Daintreei* and other plants.* This deposit occupies a denuded hollow in the Hawkesbury Sandstone, and it has been pronounced by Dr. A. S. Woodward, on the evidence of the fish, to be of Jurassic Age. It is, of course, possible that this deposit may be the equivalent in age of the water-bearing rocks of the artesian basin, in which case the latter would be newer than Triassic.

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* The Fossil Fishes of the Talbragar Beds. Memoirs Geol. Survey N. S. Wales, Palæontology No. 9, 1895.

Sydney: William Applegate Gullick, Government Printer.—1908.

Plate III.

OOMBA